Project	AtlantOS – 633211
Deliverable number	D8.3
Deliverable title	Operational real-time and forecast modelling of Atlantic albacore tuna
Description	The model SEAPODYM (Spatial Ecosystem And Population Dynamics) has now reached a degree of maturity allowing to use it for testing management scenarios and to implement operational monitoring. It is proposed to implement an operational forecast system for the Atlantic albacore tuna. The system will use physical fields (temperature, currents and primary production) from Copernicus CMEMS. The sensitivity to improved physical variables with data assimilation will be analysed and the interest of this operational production of tuna stock distributions evaluated in collaboration with colleagues involved in the management of tuna fisheries at ICCAT and FAO, and the AtlantOS fitness for this modelling analysed [D8.9].
Work Package number	WP8
Work Package title	Societal benefits from observing/information systems
Lead beneficiary	CLIOTOP SSC. Ex-officio, Collecte Localisation Satellite, FRANCE (CLS)
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Submission data	24/03/2017
Due date	31/03/2017
Comments	[in case the deliverable is late please explain why]

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1. Summary

Within the AtlantOS WP8 “Societal benefits from observing/information systems”, the use case 8.7 will demonstrate the interest of improved oceanographic variables to develop the operational modelling of Atlantic albacore tuna dynamics to simulate in real time the distribution of the species under the influence of both fishing and environmental variability. This model called Spatial Ecosystem And Population Dynamics Model (SEAPODYM) estimates stock dynamics (standard stock assessment modelling). It also predicts the spatial distribution of fish density (by cohort) and can distinguish between fishing impact and natural variability (environment and climate). The key steps and achievements to reach this challenging objective are described in this report. In particular, there is a need to revise the historical geo-referenced fishing dataset available from ICCAT and to account for the catch (fishing mortality) that has no geo-reference information. The model parameterization previously achieved at coarse resolution needs to be revised and downscaled to the higher resolution used for the operational model. Finally, the chain of automatic production needs to be developed.

The geo-referenced fishing dataset for the north and south albacore stocks has been produced and the model parameterization revised. Simulation outputs for the historical period of fishing have been evaluated based on the current knowledge of this species, the statistical fit to all fishing data and the comparison with other population dynamic model estimates. Predicted spatial dynamics and distribution are in agreement with previous studies, showing clear seasonality in the subtropical to temperate latitudes, while a continuous spawning activity is predicted in the central 0-10°S region. The model estimated total biomass of the northern stock, decreased from 0.60 to 0.40 million tonnes between 1980 and 2010; within the range of the ICCAT stock assessment. The southern stock was predicted to be twice the size of the northern stock. Due to fishing impact, the adult biomass is estimated to have declined by 40% relatively to unfished biomass at the end of 2010.

Once the ongoing downscaling phase to the ¼° resolution operational forcing is achieved for albacore, it will become possible to run the albacore pre-operational model with a start time in 1998. This is already the case for micronekton functional groups; a biological driver, essential to simulate albacore dynamics. Atlantic albacore density distributions will automatically run in near real time for the different life stages (juveniles, young immature and adult mature) and model outputs updated on AtlantOS or/and EMODNET website. Results will be presented and discussed with colleagues involved in the management of tuna fisheries at ICCAT and FAO. The impact of data assimilation in the operational ocean circulation model will be tested by comparison of two simulations using ocean forcing from a recent reanalysis (GLORYS2V4) with and without data assimilation.

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2. Introduction

The AtlantOS WP8 “Societal benefits from observing/information systems” aims at providing new information products in several GEOSS societal benefit areas (i.e. climate, disasters, ecosystems, health and fresh water, increased safety for offshore activities and coastal communities). The ambition is to deliver a suite of products that are targeted at issues of societal concern in European Member States. The WP8 pilot cases will be tangible outputs from the integration of Earth observation, *in-situ* data systems and model analyses, reanalysis and forecasts to form usable products for the above-mentioned areas of societal benefit. These end-user focused products can contribute to the EMODnet Atlantic Checkpoint Portal in terms of development of the algorithms and basic tools to evaluate fitness for purpose of the monitoring system. The present report describes the use case 8.7 dealing with the operational modelling of Atlantic albacore tuna dynamics. It is proposed that this task will demonstrate that realistic nowcast and forecast outputs of operational ocean circulation models from the Copernicus Marine Environment Monitoring Service (CMEMS) can help to implement a spatial dynamics model of Atlantic albacore and its fisheries to simulate in real time the distribution of the species under the influence of both fishing and environmental variability. The WP8.7 task is developing the reference parameterization and the pre-operational model and its chain of production and will provide outputs that could be delivered through EMODnet Atlantic portal to demonstrate feasibility.

Industrial fishing of albacore tuna (*Thunnus alalunga*) in the Atlantic started after the Second World War. Albacore is a highly-migratory species and its management is conducted through the International Commission for the conservation of Atlantic Tunas (ICCAT: www.iccat.org) for the Atlantic Ocean. Stock assessment studies are conducted by the Regional Fisheries Management Organisation (RFMO). The RFMO reconstruct past stock history based on biological knowledge, the use of fishing data (catch, effort and size frequency of catch) to account for fishing mortality and statistically fit the stock assessment models, to provide a measure of the impact of fishing and to provide key management indicators. Here, we propose a new modeling approach that combines the classical approach of population dynamics modeling used for stock assessment models and the modeling of ocean ecosystem key variables that constrain the species biology and population dynamics. This model called Spatial Ecosystem And Population Dynamics Model (SEAPODYM) not only estimates the stock dynamics as in standard stock assessment modeling, but, it also predicts the spatial distribution of fish density (by cohort) and helps to identify the impact of fishing from the natural variability due to the environment and climate variability. This new modeling approach has been made possible with the progress in oceanography, computational technology, and mathematical and statistical techniques that are offering more and more realistic numerical predictions of the ocean physical and biogeochemical state.

SEAPODYM has been extensively applied to various tuna species and tuna fisheries (Lehodey *et al.* 2008; 2012; 2013; 2015; Senina *et al.* 2008; Sibert et al 2012; Hernandez *et al.* 2014; Dragon *et al.* 2014; 2015; Nicol *et al.* 2016). With the European FP7 project EURO-BASIN, a first configuration of the model to the North Atlantic albacore has been developed with a coarse resolution and a large dataset of historical geo-referenced fishing data (catch, fishing effort and size frequencies of catch) by gear, region and flag (Lehodey *et al.* 2014; Dragon *et al.* 2015) processed from the ICCAT database (http://www.iccat.es/en/accesingdb.htm). Building from these first achievements, an operational system is currently under development to simulate in real-time and with several days forecast the spatial dynamics of this species under combined effects of environmental variability and fishing impact. The necessary steps and achievements to reach this challenging objective are described in this report. In particular, there is a need to revise the historical geo-referenced fishing dataset available from ICCAT to extend the dataset to the southern Atlantic and to account for the catch that has no geo-reference information in the ICCAT database. This is critical to account for the total fishing mortality and allows to start the operational configuration with the most realistic initial conditions of the population structure. Then the model parameterization, previously achieved at coarse resolution, needs to be revised and downscaled at higher resolution in the operational model. Finally, a chain of automatic production needs to be developed. Since the SEAPODYM model outputs are sensitive to the quality of physical and biogeochemical variables (**Figure 1**), the impact of data assimilation in the operational ocean circulation model will be also tested.

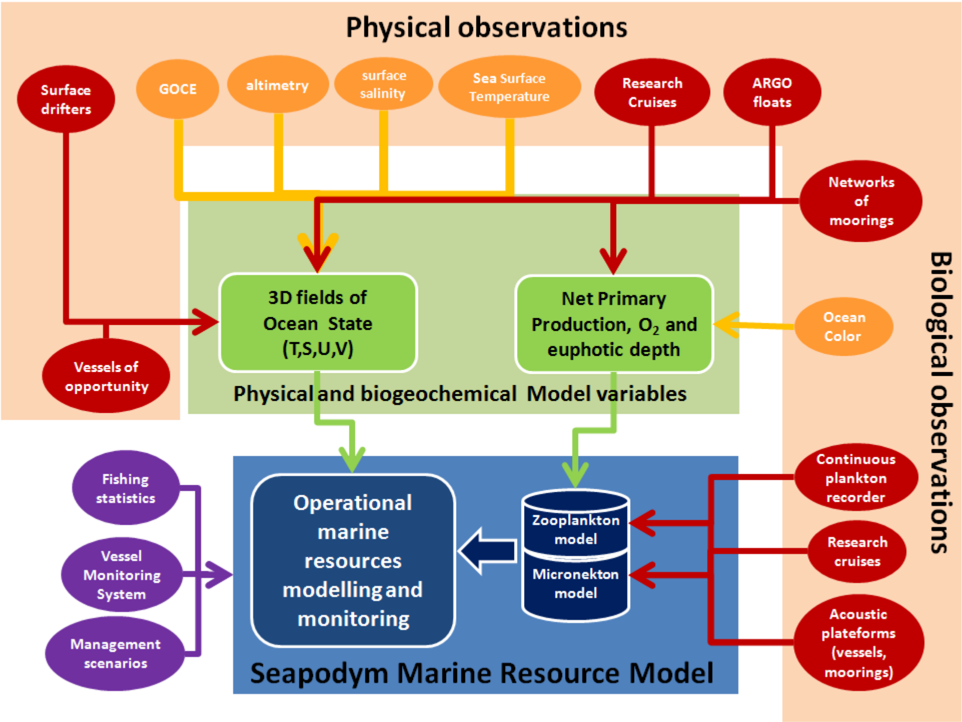

Figure 1 - Ocean *in situ* (red) and satellite (orange) data are the primary information to feed physical and biogeochemical models delivering the necessary variables for ocean ecosystem and marine resources modelling.

3. Overview on Atlantic albacore

3.1. Albacore tuna biology

Albacore tuna (*Thunnus alalunga*) is a relatively slow-growing long-living (>13 yr) species inhabiting tropical and subtropical waters of the Pacific, Atlantic and Indian Oceans, from the tropics to about latitude 55° (**Figure 2**), as well as the Mediterranean Sea. They mature at age ~4.5 years and have higher fecundity rates (Arena *et al.* 1980) when compared to other tuna species. Two distinct stocks are found in the Atlantic Ocean, in the north and south hemispheres respectively with limited interaction between the two populations. Albacore in the Mediterranean Sea is considered an independent stock. The vertical distribution of albacore has been observed directly by electronic tagging (Domokos *et al.*, 2007) or indirectly by the depth of longline hooks (Suzuki *et al.* 1977). Albacore inhabit the epi- and mesopelagic oceanic layer. Juvenile albacore inhabit shallower depths than adults. The species has limited tolerance to poorly oxygenated waters with a lower tolerance limit around 3.7 mL L^{-1} dissolved oxygen concentrations and a lethal threshold below 1.2 mL L^{-1} (Graham *et al.*, 1989). Mature fish spawn in warm waters (e.g., offshore Venezuela, the Sargasso Sea and in the Gulf of Mexico) and juveniles seem to spend the winter in subtropical areas. Based on fishing observer records, spawning time and area for the northern stock was determined to occur from March to April in the area SW of the Sargasso Sea (Luckhurst and Arocha 2016). In spring, 1 year old immature North Atlantic tuna (~40 cm) migrate to feeding grounds (e.g., the NE Atlantic) where they are caught by fisheries (Trenkel *et al.* 2014). In late October they start to migrate toward the mid-Atlantic. A migration route of the northern stock follows a pathway along the south of Portugal, the Canary Islands and the Azores (Arrizabalaga, 2003). Adult albacore can grow to 40 kg (120 cm), with males growing larger than females (Santiago and Arrizabalaga, 2005). Growth is rapid in early life stages and slows with age. Past studies indicate an opportunistic diet, with a high diversity of prey species identified in stomach contents that includes crustaceans, fish and cephalopods associated with the epi- and meso- pelagic layers. Albacore feed throughout the day and night in the epipelagic layer. They can dive into the mesopelagic and/or bathypelagic layers to feed during the day.

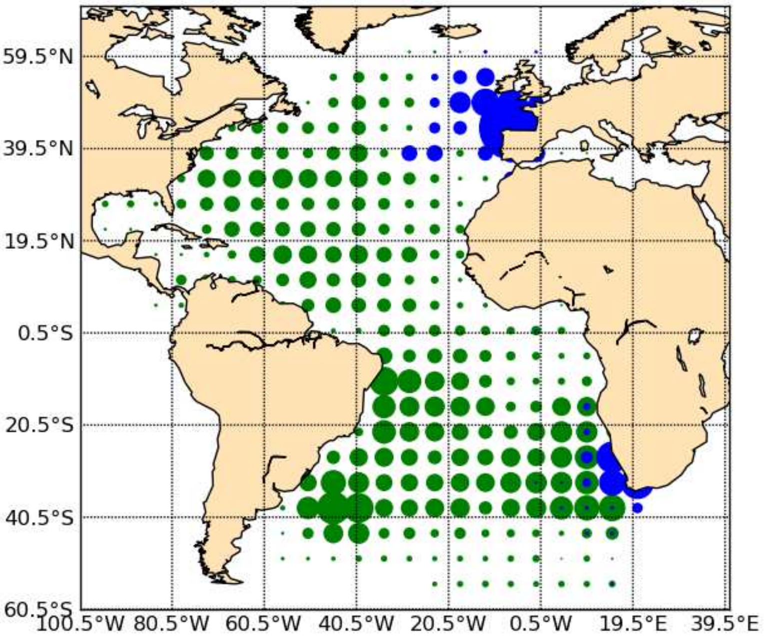

Figure 2 - Geographic distribution (5°x5°) of albacore mean annual catch by major gears for 1987-2014 before scaling to nominal catch level (based on ICCAT database). Longline in green and surface gears (bait boats and trolling boats) in blue.

3.2. Atlantic Albacore fisheries

For the last 60 years, albacore tuna has been exploited in the Atlantic by various fishing gears. The northern stock of albacore has been exploited all year round by longline fisheries, mainly from Japan, Taiwan

Republic of China, and Korea, targeting subadult and adult albacore. Recent catch rates have showed declines mostly due to a decrease in landings by Chinese Tai Pei fleet and a decline in Japanese caught Albacore as by-catch. European fisheries (Spain, France, Ireland and Portugal) are surface fisheries targeting mainly immature and sub-adult fish in the Bay of Biscay and adjacent waters of the northeast Atlantic (Celtic Sea) in summer and autumn, and also around Madeira and the Azores (Portuguese fisheries). All together these fisheries represented 98% of the total catch declared to ICCAT between 1960 and 2008 for the northern stock (**Figure 2**). Caribbean Countries (Venezuela, Panama, Cuba, Trinidad and Tobago, Belize, Dominican Republica, Grenada, Barbados, Santa Lucia and UK Bermuda), contribute to the remaining catch (1.9%), mostly by longlining. Total reported landings in the North Atlantic show a downward trend since 2006 (~37,000 t) reaching a minimum of about 20,000 t in 2011 (Figure 2). This was mostly due to the decrease in baitboat catches (~60% reduction in weight) and troll (~65% reduction) fisheries in the Cantabrian Sea (Spanish fleet). Since 1986, the longline fishery (mostly Chinese Taipei and Japan) catch decreased due to a shift toward tropical tuna for the sashimi market; as illustrated by the decline of the albacore/bigeye price ratio from ~1/1 in the 1960s to ~1/3 in the 2000s (Fonteneau, 2008). Since 2012, the overall catches increased slightly to a maximum of about 26,500 mt in 2014, caused mostly by an increase in European trawl catches, the baitboat fisheries of Canary, Azores and Madeira and the Japanese and Chinese Taipei longline fisheries (ICCAT 2016).

The Southern Atlantic albacore fisheries are dominated by the surface baitboat fleets from South Africa and Namibia, and the longline fleets from Brazil and Chinese Taipei. The overall catch of the Southern Atlantic albacore fisheries oscillated near ~24,000 mt between 2006 and 2012. This was followed by a large drop to less than 14,000 t (more than 40% reduction) in 2014. This decrease is linked to a catch reduction of the major fisheries (Longline: Chinese Taipei, Japan, and Brazil; Baitboat: South Africa, Namibia, and Brazil).

In recent years, catches were below the Total Allowable Catch (TAC) defined by ICCAT (**Figure 3**).

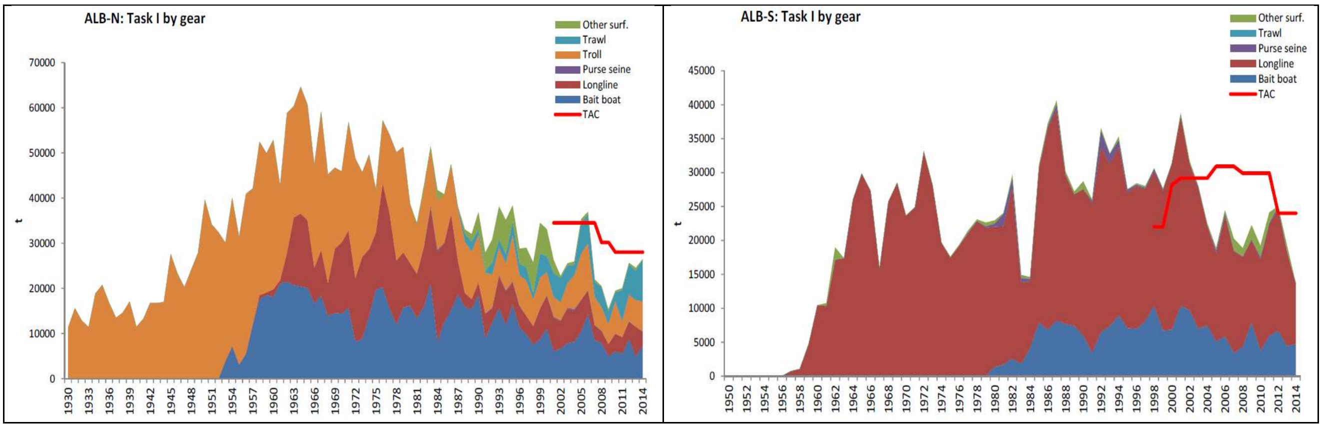

Figure 3 - Accumulated annual catches of albacore by major gear (1950-2014) in the Northern (left) and Southern (right) hemispheres (from IOTC 2016). Red line denotes the Total Allowable Catch (TAC).

3.3. Stock Status

The Atlantic Albacore stock assessment was revised in 2016 (ICCAT 2016). The previous assessment in 2013, used various models (MFCL, SS3, VPA and ASPIC), with a wide range of uncertainty, but with an overall agreement between models that northern stock was overfished, but not currently undergoing overfishing, i.e., current fishing effort is not above the fishing effort estimated for the maximum sustainable yield. The models estimated a drop in stock biomass between 1930 and circa 1990. Fishing mortality reached a peak circa 1990. However, an upward trend in biomass is evident circa 2000. The 2016 update assessment used a production model framework. Results indicate a biomass drop between the 1930s and the 1990s and a recovery since then. The stock is assumed to have recovered to levels above the Biomass at Maximum sustainable Yield (BMSY). The magnitude of the recovery is not well determined and remains sensitive to many different assumptions. For the southern stock, a non-equilibrium surplus-production model (ASPIC) and a Bayesian Surplus Production (BSP) model were used with catch and several CPUE time series (ICCAT 2016). Six of the eight scenarios tested indicated that the stock is not overfished. Northern Albacore stock annual TAC was 34,500 tons until 2007 when it reduced to 26,000 mt. In 2016, the Southern stock TAC was set at 24,000 mt.

4. Modeling the past history of Atlantic albacore

4.1. SEAPODYM

SEAPODYM is an example of an ecosystem and population dynamics model that can be plugged into operational ocean circulation models in order to simulate the spatial dynamics of mid- and upper- trophic levels with functional groups of the mid-trophic levels and age-structured population dynamics of large pelagic species such as tunas.

The main features of the model are:

- Forcing through off-line coupling to environmental variables such as temperature, currents, primary production and dissolved oxygen concentrations;
- Prediction of micronektonic prey functional group distribution (Lehodey *et al.* 2010; 2015), and age-structured predator (tuna) populations (Lehodey *et al.* 2008);
- Prediction of catch and size-frequency of catch by fleet using observed fishing effort;
- Parameter optimization based on data assimilation techniques (Senina *et al.* 2008, 2015).

SEAPODYM simulates fish age-structured population dynamics with length and weight relationships obtained from independent studies. Density of larvae recruited in the first cohort results from a local stock-recruitment relationship and the favorability of the spawning habitat index combining temperature preference and coincidence of spawning with presence or absence of predators and food for larvae. After the spawning, different life stages are considered: larvae, juveniles, immature and mature adults. At larvae and juvenile phases, fish drift with currents; later on they become autonomous, whereby in addition to the currents velocities their movement has additional component linked to their size and the habitat quality. The feeding habitat is based on the accessibility of tuna to the groups of micronektonic forage. Food requirement and food competition indices are computed to adjust locally the natural mortality of cohorts, based on food demand, accessibility to available forage components and biomass of other tuna cohorts. From the pre-defined age at first maturity fish start spawning and their displacements are controlled by a seasonal switch between feeding and spawning habitats, effective outside of the equatorial region where changes in the gradient of day length are marked enough and above a threshold value. The last age class is a "plus class" where all oldest individuals are accumulated.

The model simulates the spatially explicit distribution of age-structured fish population from larvae to adult in an Eulerian framework. The dynamics of both forage (micronekton) and predator species (tuna) are driven by local environmental forcing predicted by coupled physical–biogeochemical models. The model parameters, controlling movement and habitat characteristics, are estimated with a maximum likelihood estimation approach that minimises the differences between the observed and predicted fishery values from multiple fisheries (Senina *et al.* 2008). Data used are georeferenced catch, fishing effort, catch per unit of effort (CPUE) and the size frequencies of catch. Catch by age are predicted based on the observed fishing effort and a catchability coefficient and a selectivity function characterising the fishing fleet. Catch is obviously also used to account for fishing mortality.

SEAPODYM predictions, i.e. density maps of larvae, juveniles, young and adult fish cohorts, have the same resolution as the environmental forcing. Catch and CPUE are computed at the time step of the simulation, and length frequencies are aggregated quarterly for comparison with observations. This model has now reached a degree of maturity allowing its use to test management scenarios and to implement operational monitoring. The architecture of this operational application, the approach for its parameterization and first preliminary results are presented in the following sections.

4.2. Operational modeling configuration

The implementation of the operational model SEAPODYM for the Atlantic albacore necessitates a series of technical steps that are summarized in **Figure 4** and discussed in detail below.

4.2.1. Model optimization and validation

Rebuilding the history of albacore tuna fisheries over the “industrial fishing period” is necessary to provide initial conditions of the operational model. The hindcast phase of the model run provides a learning period to estimate the population dynamics and the fisheries parameters. Several series of optimization experiments were conducted with SEAPODYM for South Pacific (Lehodey *et al.* 2015) and North Atlantic albacore stocks (Dragon *et al.* 2015). This parameterization was a first step to start the virtuous loop of improvement shown in **Figure 4**. Due to computational constraints, and the need to simulate long historical time series to rebuild the history of fishing, the optimization experiments were conducted at a coarse resolution of 1° or 2° and a monthly time step with physical (temperature and currents) and biogeochemical (primary production, euphotic depth and dissolved oxygen concentration) variables provided by a coupled ocean physical-biogeochemical model (see section 4.4 below).

The physical-biogeochemical forcing simulated the zooplankton and micronekton functional groups. Additional optimization experiments were conducted with an updated fishing dataset for the Atlantic Ocean in order to obtain the best model parameterization for albacore tuna using the maximum likelihood estimation (MLE) approach implemented with SEAPODYM. Once the new optimal set of parameters was estimated, the outputs were analysed and used to evaluate the model.

When fishing data lacked of accuracy, it was omitted in the optimization approach, but, was used separately to account for total fishing mortality.

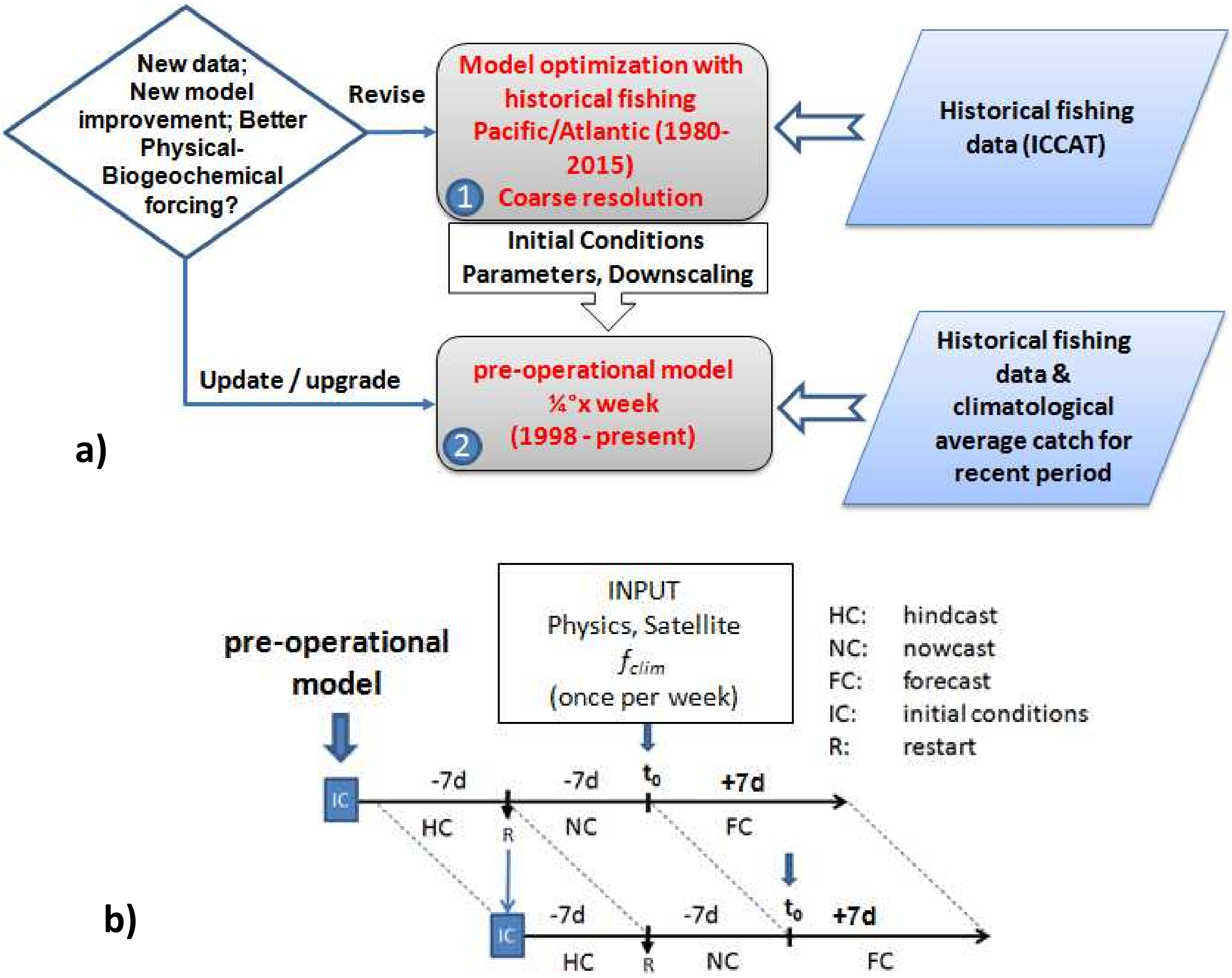

Figure 4 - Workflow shows the different steps and model configurations used to run the operational Atlantic albacore model. a) Model optimization at coarse scale with historical fishing data and downscaling to the higher resolution configuration of the pre-operational model. b) The pre-operational model provides initial conditions (population structure by cohort) of the tuna species of the operational chain of production; every week the production automatically generates three weekly time steps to include a hindcast, a nowcast, and a forecast that uses climatological fishing effort and catch.

4.2.2. Downscaling to global configuration

Once the optimal solution is achieved with the new Atlantic albacore fishing data set and its multiple fisheries, the initial conditions of the species population (density by cohorts and space at a given date) are used to seed the operational global model. This configuration has a model domain at an intermediate space x time resolution of ¼° x week and uses physical inputs from GLORYS ocean simulation system (www.mercator-ocean.fr/en/science-publications/glorys/). The change of forcing models and resolution requires to apply a downscaling approach for rescaling optimal parameters to the new environmental model configuration (**Figure 4**, step 2). This step is conducted in the MLE framework of the model with the objective to estimate habitat distributions similar to those achieved with the first configuration. A second optimization experiment is then used to rescale fish movements and fisheries parameters, keeping all other parameters fixed or directly scaled to the new time step resolution.

4.2.3. Chain of production

The chain of operations starts with the weekly delivery of physical and biogeochemical raw data. Once the physical and biogeochemical variables are received, a phase of pre-processing reduces the number of vertical layers by averaging the values according to the definition of vertical boundaries (linked to the euphotic depth; e.g., Lehodey *et al.* 2015). The micronekton model runs in parallel to simulate the production and biomass of the functional groups, and finally it is the tuna model to simulate fish cohorts density distributions. This chain of production is duplicated, once with fishing effort and catch (dummy fisheries) and once without fishing effort, in order to provide management indicators on fishing impact.

As a result, the SEAPODYM operational model provides a weekly simulation output for micronekton and albacore tuna species over a period of three time steps to include a hindcast week, a nowcast week and a forecast week. The hindcast is archived to produce a historical time series from the selected start date of the operational model. The forecast is based on the physical ocean forecast (e.g., COPERNICUS CMEMS) and the persistence of the last primary production map.

In the absence of fishing data for the current period, the models use a fishing effort climatology based on the last available five years. This should account for the average fishing mortality and help avoid a biomass drift that would be predicted in the absence of fishing data.

4.3. Environmental forcing variables

The SEAPODYM model requires temperature and horizontal current data derived from physical ocean models, primary production (PP) either derived from satellite data or predicted from biogeochemical model, and dissolved oxygen concentration either from a climatology or a biogeochemical model. Information on the euphotic depth (*Zeu*) is also required to define the three vertical biological layers of SEAPODYM.

4.3.1. Hindcast 1° x month forcing (1972-2011)

For the coarse resolution configuration, used for optimization, we used a hindcast simulation (1972- 2011) from the NEMO ocean model (www.nemo-ocean.eu/), a model forced by ERA40-INTERIM atmospheric reanalysis (atmospheric temperature, zonal and meridional wind speeds, radiative heat fluxes, relative humidity, and precipitation) and corrected with satellite data (Dee *et al.* 2011). The Nucleus for European Modelling of the Ocean or NEMO model was coupled to a biogeochemical model called PISCES (Pelagic Interaction Scheme for Carbon and Ecosystem Studies; Aumont *et al.* 2015). All forcing variables were interpolated on a regular grid and similar time step prior to their use in the SEAPODYM simulations.

4.3.2. Pre-operational ¼° x week forcing (1998-2016)

The pre-operational system, at ¼° x week resolution, uses physical fields, satellite derived primary production and euphotic depth data from Mercator-Ocean / Copernicus CMEMS. There is a lack of historical synoptic datasets available for the ocean colour (SeaWiFS) prior to 1998. Ocean reanalyses with satellite derived primary production are therefore unavailable to simulate albacore tuna dynamics with SEAPODYM before 1998.

The first pre-operational simulation uses a free (i.e. without data assimilation) GLORYS ocean hindcast simulation for the period 1998-2015. Results achieved with this first configuration will be used as a bench mark for the later comparison with the GLORYS reanalysis using data assimilation.

Unlike a hindcast simulation driven only by atmospheric conditions, an ocean reanalysis assimilates oceanic variable observations derived from satellite (Sea Level Anomalies, Sea Ice Concentration and Sea Surface Temperature) or *in-situ* (temperature and salinity profiles) measurements, to provide a more realistic prediction. In its final operational configuration, the SEAPODYM albacore model should use both the GLORYS reanalysis and its operational version, i.e. the Mercator-Ocean (PSY3) model, or the 1/12° version available on CMEMS degraded to ¼°. Primary production and associated euphotic depth used in this configuration are derived from ocean color data using the VGPM model of Behrenfeld and Falkowski (1997), while a climatology from the World Ocean Atlas (Garcia *et al.*, 2010) is used for the dissolved oxygen concentration.

4.4. Historical fishing datasets

As noted above, the structure of the albacore population in the model heavily depends on the historical fishing dataset to force the model. An initial study allowed the development of a georeferenced fishing dataset for north Atlantic fisheries (Lehodey *et al.* 2014) based on ICCAT database (http://www.iccat.es/en/accesingdb.htm). Fisheries were defined by fishing gear, the fishing ground and the fishing country. In total, thirteen fisheries were defined for the period 1956-2010. However, depending on the year, spatial locations were only available for 20% to 50% of the ICCAT recorded landings (**Figure 4** in Lehodey *et al.* 2014).

This first fishing dataset was extended with fisheries from the south Atlantic and then georeferenced data were raised to the level of nominal catch to provide the best possible account of total fishing mortality over the entire historical fishing period. **Table 1** below lists all fisheries. In addition to the north albacore fisheries (Lehodey *et al.* 2014), today surface baitboat fleets exist from South Africa and Namibia along with longline fleets from Brazil and Chinese Taipei. After the data was screened, geo-referenced data were raised to the nominal catch level. For each fleet, a corresponding dummy fishery was created including missing catch distributed proportionally to the existing available monthly georeferenced data (**Figure 5** and appendix). The catch of these dummy fisheries have been combined by fishing gear into four main dummy fisheries (D201 to D204). There is still some differences between the total annual nominal catch and the geo-referenced catch (**Figure 5**) which is due to small fisheries (e.g. Caribbean Countries) and fishing gears (gillnet, handline, sport fishing, etc.) and is not included in this analysis.

Finally, it was deemed necessary to create an average monthly fishing effort (or catch) distribution by fishery (i.e. a climatological fishing effort) based on the five most recent years of available data to account for fishing mortality in current year when fishing statistics are not publically available. Otherwise the total release of fishing pressure would create an artificial and rapid increase in the stock biomass.

Length frequencies of catch for Atlantic albacore were available from the ICCAT database. Data was extracted according to the definition of fisheries above with a quarterly temporal resolution and spatial resolutions from 1°x 1° to 10°x 20°. Given that very few albacore reach a size above 130 cm (Le Gall 1974; ICCAT 2016), this value was set as a maximum threshold and samples with length frequency data above this

130 cm were removed to avoid incorrect data use due to species misidentification (for details see Lehodey *et al.* 2014).

Table 1 - Atlantic albacore fisheries 1950-2014.

FISHERY	COUNTRY_NAME	GEAR	TIME_PERIOD	RESOLUTION	EFFORT_UNIT
L1	JAPAN	LL	1950-1972	5	NO.HOOKS
L2	JAPAN	LL	1973-2014	5	NO.HOOKS
L3	USA	LL	1950-2014	1	NO.HOOKS
L4	TAIWAN-SUBTRO	LL	1950-1986	5	NO.HOOKS
L5	TAIWAN-TRO	LL	1950-1986	5	NO.HOOKS
L6	TAIWAN-SUBTRO	LL	1987-2014	5	NO.HOOKS
L7	TAIWAN-TRO	LL	1987-2014	5	NO.HOOKS
L8	KOREA	LL	1950-1979	1	NO.HOOKS
L9	KOREA	LL	1980-2014	5	NO.HOOKS
L10	BRAZIL	LL	1950-2014	5	NO.HOOKS
T11	FRANCE	TROL	1950-2014	1	D.FISH
T12	FRANCE	MWTD	1950-2014	1	NO.SETS
T13	SPAIN	TROL	1950-2014	5	D.FISH
B14	SPAIN	BB	1950-2014	5	D.FISH
B15	SOUTH-AFRICA	BB	1950-2014	1	D.AT SEA
B16	NAMIBIA	BB	1950-2014	1	NO.POLES
D201	D101 to D110	LL	1950-2014	5	NO.HOOKS
D202	D111 and D113	TROL	1950-2014	1	NO.HOOKS
D203	D112	MWTD	1950-2014	5	NO.HOOKS
D204	D114 to D116	BB	1950-2014	1	NO.HOOKS

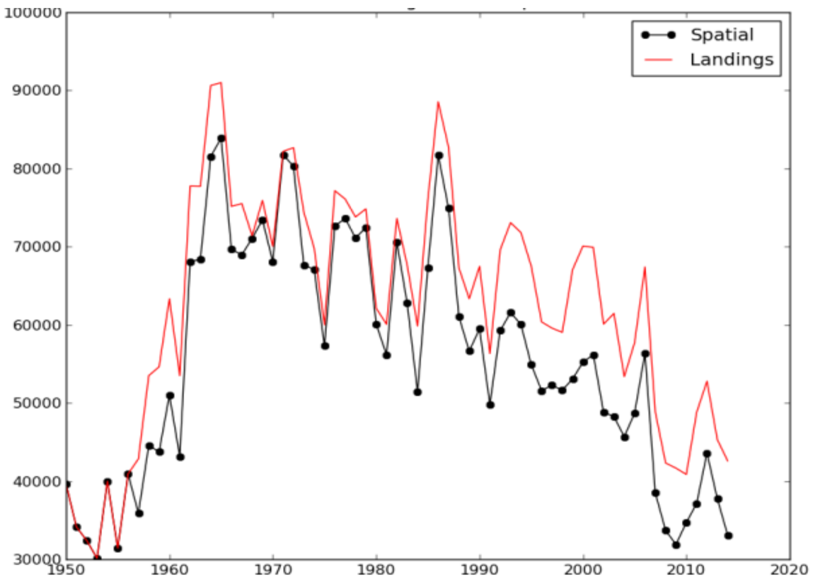

Figure 5 – Comparison of total catch by all the Atlantic albacore fisheries (Table 1) after scaling to nominal catch level (based on ICCAT database).

5. Results

5.1. Albacore population parameterization

The structure of the population was defined with 53 quarterly cohorts, the last one being a “plus cohort” accumulating older fish. The age at first maturity was set to 4.5 years, i.e. 54 months (Santiago and Arrizabalaga, 2005). In addition to this age structure, the model takes into account 4 different life-stages: larvae (0 to 1 month), juveniles (1 to 3 months), young immature fish (3 to 54 months) and mature adult fish (over 54 months) by describing the dynamics of each stage with different equations (Lehodey *et al.* 2008). The optimized solution achieved during the EuroBasin project (Dragon *et al.* 2015) has been used and revised with the new INTERIM forcing and updated SEAPODYM version (Senina *et al.* 2016) and the domain is extended to include south Atlantic stock and fisheries.

5.1.1. Growth, Natural mortality and recruitment

The growth of albacore tuna is simulated with one length and one weight coefficient by cohort obtained from independent studies (Bard 1981; Gonzales-Garces and Farina-Perez 1983). According to Santiago and Arrizabalaga (2005), age at first maturity was set to 54 months that approximately corresponds to fish of 84 cm in fork-length (Lehodey *et al.* 2014).

In SEAPODYM, the mortality mechanism depends on five parameters (Table 2; **Figure 6**). The mortality rate is estimated to decrease rapidly in the early life stage, from > 0.06 mo^{-1} on average in the first year of life to a minimum of 0.02-0.04 mo^{-1} (0.24-0.48 yr^{-1}) between years three to ten, followed by a clow increase in older cohorts (**Figure 6**). In recent ICCAT stock assessment studies, natural mortality rate is fixed to 0.3 yr^{-1} (0.025 mo^{-1}, ICCAT 2016).

Recruitment in SEAPODYM occurs locally in the first cohort (larvae; age < one month) proportionally to the spawning index and a Beverton-Holt stock-recruitment relationship linking the number of recruits to the spawning biomass (i.e. adult fish) present in the cell. This B-H relationship is defined by two parameters. The asymptotic value is correlated to the natural mortality estimates. The slope value was estimated by Dragon and co-workers (2015). The spawning index combines the effects of water temperature, abundance of prey larvae and density of larval predators (i.e. micronekton in the surface layer).

5.1.2. Spawning and feeding habitats

The spawning habitat index is estimated to be optimal for Sea Surface Temperature (SST) at 26.05°C (SE: 1.5°C). Taking into account the dynamics and drifting with currents, the resulting average distribution of larvae occurs mainly within a SST range of 23° to 29°C. Adult fish migrate to favourable spawning grounds by following temperature gradients that lead to their optimal spawning temperature. The seasonal timing of spawning migration was estimated to peak at Julian date 70 (12th March, or 11th during leap year), i.e. before the boreal spring equinox.

The feeding habitat index combines sensitivity to temperature and dissolved oxygen, defining accessibility to prey (micronekton) in surface, sub-surface and deep layers. After the larval stage, the optimal temperature in the water column inhabited by the fish is estimated to decrease from ~23°C to ~14°C for the oldest/largest fish (**Figure 6**). Estimated threshold value (4.12 mL.L^{-1}) and steep slope of the oxygen functional relationship indicate a high sensitivity of albacore to oxygen levels in its habitat.

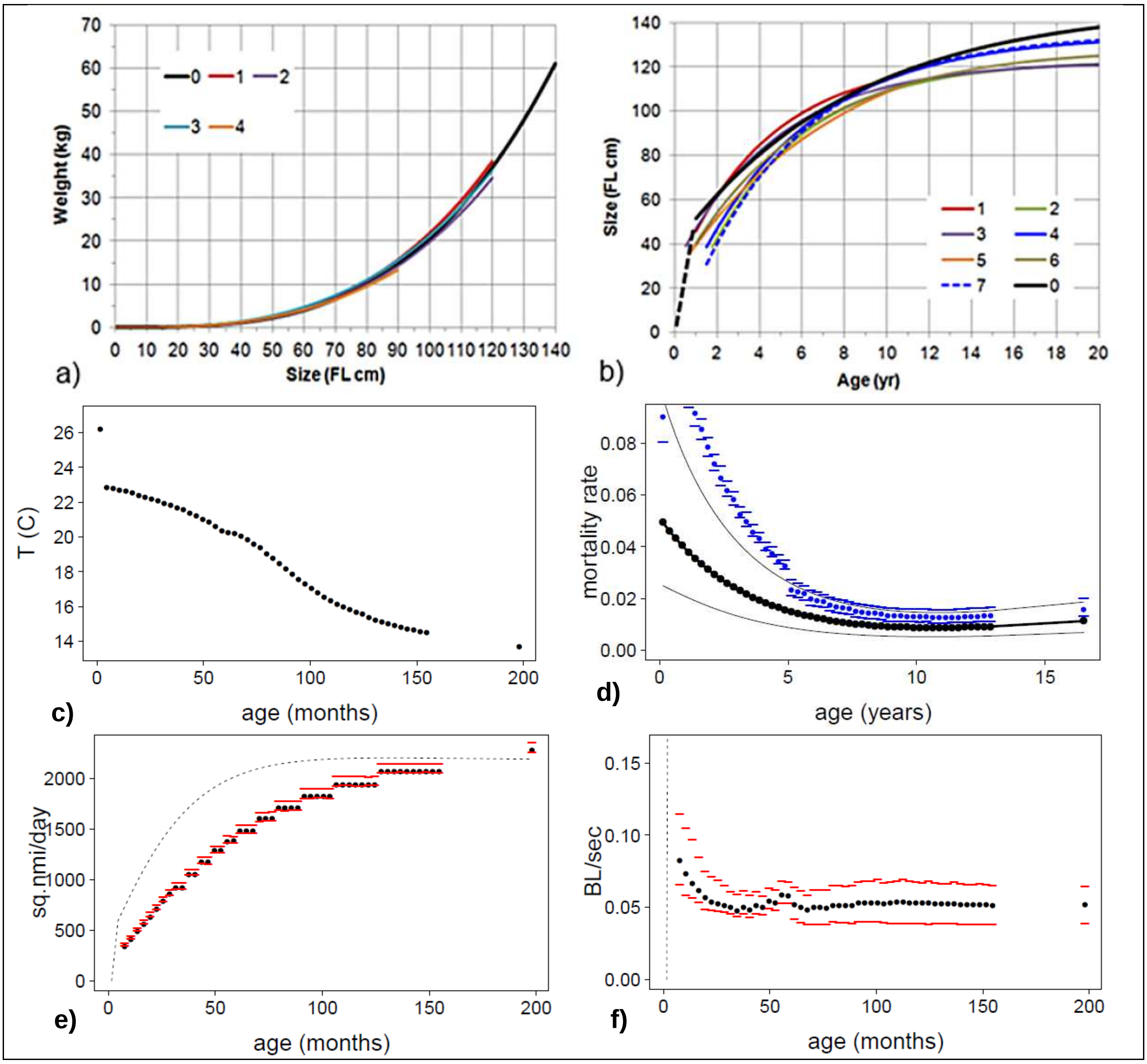

Figure 6 - Parameterization of functional relationships used in SEAPODYM to model the albacore population dynamics. For growth (a and b) see references in Lehodey *et al.* (2014); thermal habitat (c), natural mortality (d), diffusion (e) and advection (f). For d, theoretical values (black dots) are compared to coefficients weighted by the cohort density to provide a more meaningful metric taking into account the local impact of natural mortality. For e and f, coefficients are also weighted by the cohort density.

5.1.3. Movement

Fish movements depend on two parameters controlling diffusion and directed movements (advection). The mean maximum diffusion rate reaches 2000 nmi^2 month^{-1}. The mean maximum sustainable speed (V_{max} in body length per second, BL.s^{-1}) remains below 0.15 BL.s^{-1}, with a theoretical maximum value estimated to its lower boundary value (V_{max} = 0.95 BL.s^{-1}). The speed decreases with age (size) together with the habitat gradient, due to increasing accessibility to forage biomass of deeper layers. However, it should be noted that based on previous optimization experiences, the movement may be underestimated due to the coarse resolution and lack of direct information (e.g., tagging data) for the MLE approach (Senina *et al.* 2016).

Table 2 - Model parameterization. Boundary (min-max) and initial values are given with the final estimate value. "f" stands for fixed value and "r" for released. Fishery parameters (catchability and selectivity), not shown, were estimated for all fisheries.

	Parameter	**Description**	**Min**	**Max**	**Initial Value**	**Final value**
Mortality	M_p	Maximal mortality rate due to predation	0	0.25	0.0511	f
	e_p	Slope coefficient defining the rate of decrease of predation mortality with age	0.005	0.26	0.0142	0.226
	M_s	Minimal value of senescence mortality	0	0.005	1.83e-5	7.3 e-6
	e_s	Slope coefficient in senescence mortality	0.1	2	1.5781	1.378
	ε	Variability of mortality rate with habitat index	0.05	3.1	2.4099	2.499
B-H	R	Maximal number of larvae at large spawning biomass of adults	0.001	0.015	0.0107	0.041
	b	Slope coefficient in Beverton-Holt function	0.005	2.0	0.4767	f
Habitats	θ_{sp}	The day of the year, when the spawning season peaks	40	90	79.284	70.28
	θ_{ss}	The ratio day length/night length, which marks the beginning of the spawning season	0.95	1.125	1.0976	1.0198
	σ_0	Standard deviation of the Gaussian for spawning temperature	0.2	1.75	1.4998	1.499
	T_0	Optimal spawning temperature (mean of the Gaussian)	24	26	24.961	26.05
	σ_K	Standard deviation in thermal feeding habitat index	1	4.5	4.0	3.0
	T_K	Optimal temperature of feeding habitat for oldest tunas	5.9	15	6.0	14
	γ	Slope coefficient in the oxygen sigmoïd function	1e-5	0.15	1e-5	1e-5
	$\hat{O}$	Critical value of dissolved oxygen affecting the habitat index	2	6	4.1203	4.12
Movement	D_{max}	Diffusion coefficient for the species	0	0.125	0.1133	0.1134
	V_{max}	Theoretical maximal sustainable speed (in body length/s)	0.95	3	0.9501	0.95001
	C	Slope coefficient between diffusion and habitat	0	1	6.369e-7	f
Fishery	q	Constant catchability coefficients for each fishery	0	0.01	-	r
	s	Steepness of selectivity logistic and sigmoïd function or standard deviation for asymetric Gaussian function	0	16	-	r
	l_{cr}	Threshold length in sigmoïd function, mean length in asymetric Gaussian function	55	125	-	r
	l_K	Lowest selectivity for large fish in case of asymetric Gaussian function	0	1	-	r

5.2. Model Validation

5.2.1. Spatio-temporal fit to catch data

The model outputs show a good fit in predicted catch spatially and temporally (**Figure 7**), especially in the main fishing ground where maximum catch occurred over time. The fit is degraded on the borders of the catch distribution, in relation to the low level of catch and a lack of resolution near the coast.

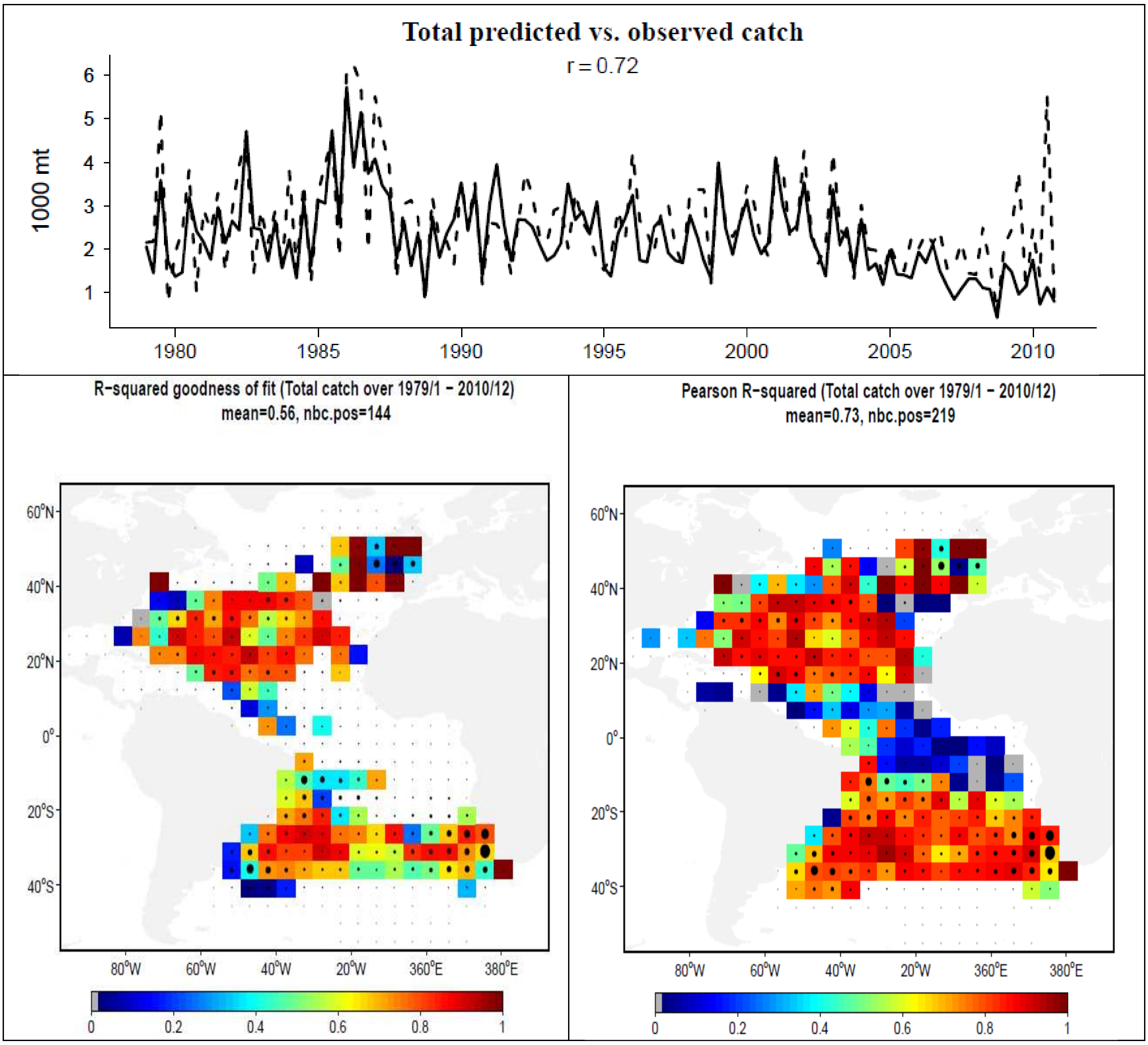

Figure 7 – Fit between observed and predicted historical catch data 1979-2010. Top: Time series of predicted (continuous line) and observed (dotted line) total monthly catch. Bottom left: Map of *R*2 goodness of fit. Bottom right: Map of Pearson-R2 goodness. Black circles are proportional to observed catch and white squares indicate negative correlation between observations and predictions.

The correlation coefficients between observed and predicted catch time series are high overall and range between [0.21; 0.99] for the complete catch time series. The best fit is obtained for the tropical and subtropical Taiwanese longline fisheries targeting albacore, while it is the lowest for the Japanese longline fishery that rapidly focused on bigeye tuna and for which albacore is more a by-catch (**Figure 8**). The model also gets good scores for all southern Atlantic fisheries; longline and surface (**Figure 8**).

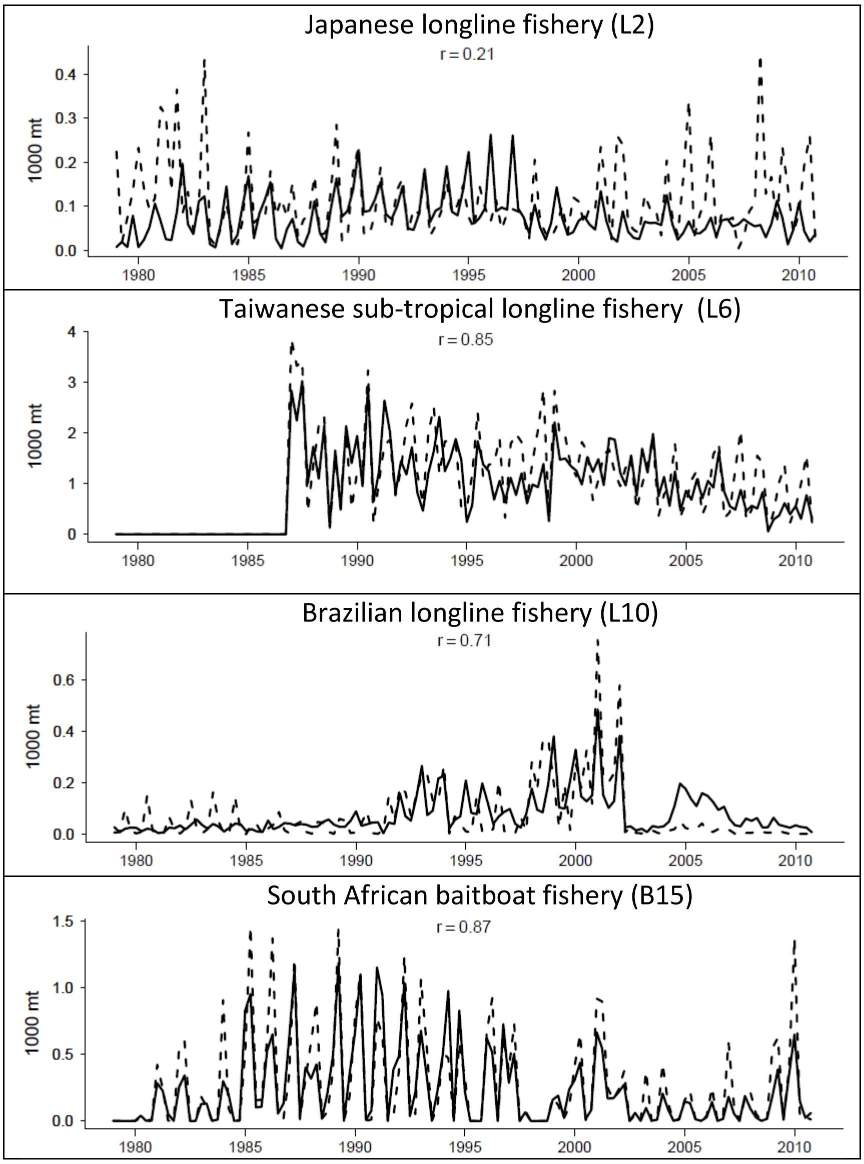

Figure 8 – Fit between observed (dotted line) and predicted (continuous line) historical catch data 1979-2010 for selected fisheries.

5.2.2. Stock estimates and fishing impact

The total biomass of Atlantic albacore (northern and southern stocks) is estimated to decrease from ~2.0 million t (Mt) in 1980 to 1.2 Mt in 2010, and from 0.6 to 0.4 Mt and ~1.3 to ~0.8 Mt for the northern and southern stocks respectively (**Figure 9**). This corresponds to a fishing impact decrease of 40% in the adult biomass relatively to unfished biomass in 2010 (**Figure 10**). The fishing impact and the biomass trend stabilised post 2005. The north albacore stock biomass estimate of 400,000 mt in 2010 is within the range of the last biomass estimate proposed in the stock assessment by ICCAT (2016) (**Figure 9**). The southern stock is predicted to be twice the size of the northern stock. There is no absolute biomass estimate from ICCAT for this stock for comparison.

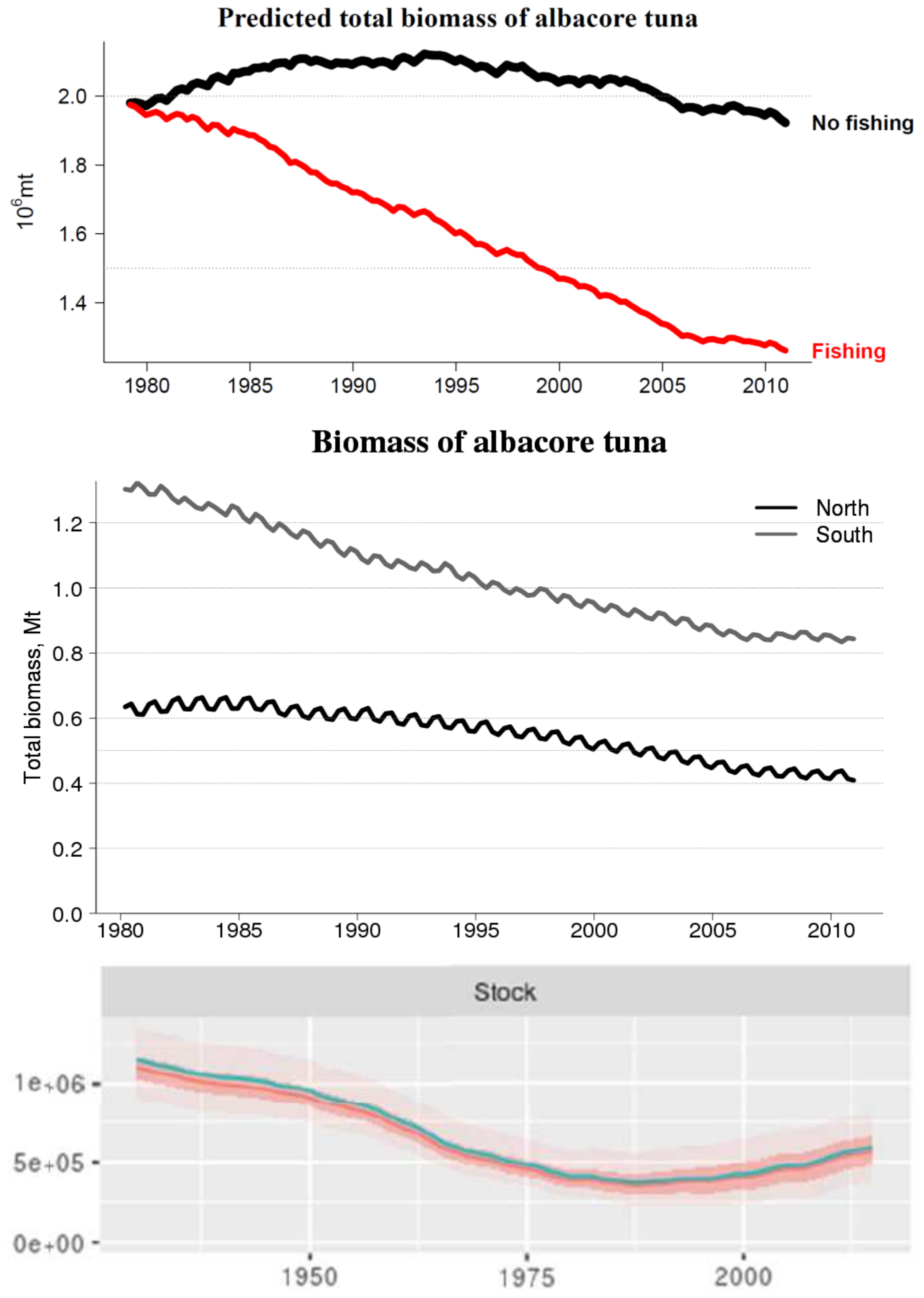

Figure 9 – Biomass estimates of Atlantic albacore. Top: biomass with and without fishing effort. Middle: total biomass with fishing in the north and south Atlantic (latitude boundary set to 5°N as for ICCAT studies). Bottom: Biomass estimate from ICCAT (2016) for the North Atlantic stock.

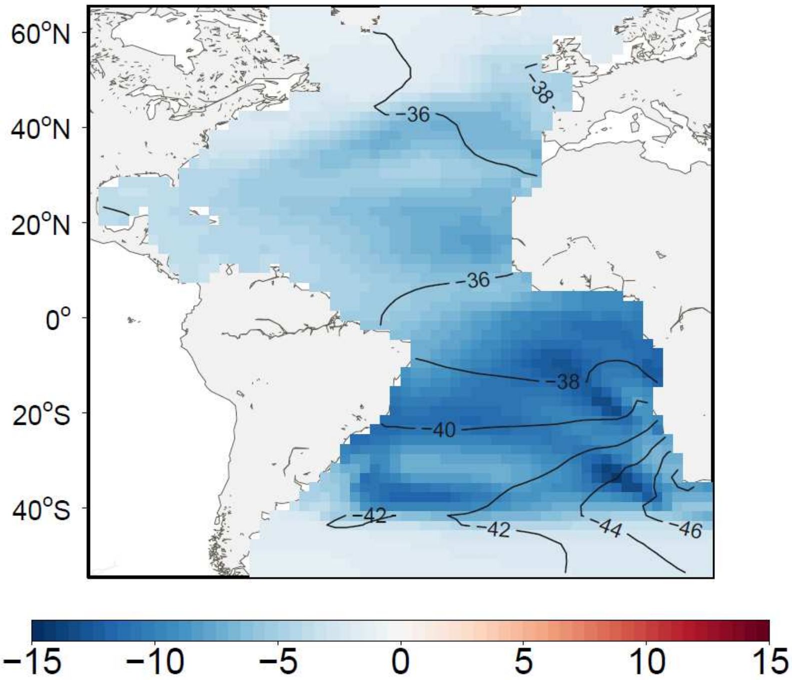

Figure 10 – Impact of fishing on Atlantic albacore. Map showing the reduction of biomass in adult (spawning) albacore for the year 2010. The colour scale highlights the reduction of biomass (kg km^{-2}) in the map and the isopleths displays the percentage decline.

5.2.3. Variations in spatial dynamics of albacore at different life stages

In agreement with previous studies (Goni and Arrizabalaga 2005), juvenile albacore tuna are predicted in warm surface waters whereas adults inhabit cooler and deeper waters. The model predicts a marked seasonal variability in the spawning grounds and subsequent distribution of juvenile (age 1-3 month) recruits (**Figure 11**). A continuous spawning activity is predicted in the central 0-10°S region. A seasonal concentration of juveniles occurs in the 2nd and 3rd quarter of the year and is clearly related to the Canary upwelling system off the northwest Africa coast (**Figure 10**) extending far offshore. Another large concentration of small juvenile albacore appears in the 3rd quarter of the year in the NW sub-tropical southern Atlantic in the Gulf Stream path; the Sargasso Sea, a known albacore spawning ground (Le Gall 1974; Nishikawa *et al.* 1985). In the southern hemisphere, with the opposite seasonality, an area predicted to have high juvenile concentration is along the coast of Brazil from Cabo Frio to south of 20°S.

Predicted seasonal distributions of adult fish show a maximum extension in northern latitudes during the 3rd and 4th quarter of the year. A southward movement to subtropical regions are predicted in the 1st and 2nd quarter (winter to spring). An opposite seasonal pattern was simulated for the southern hemisphere.

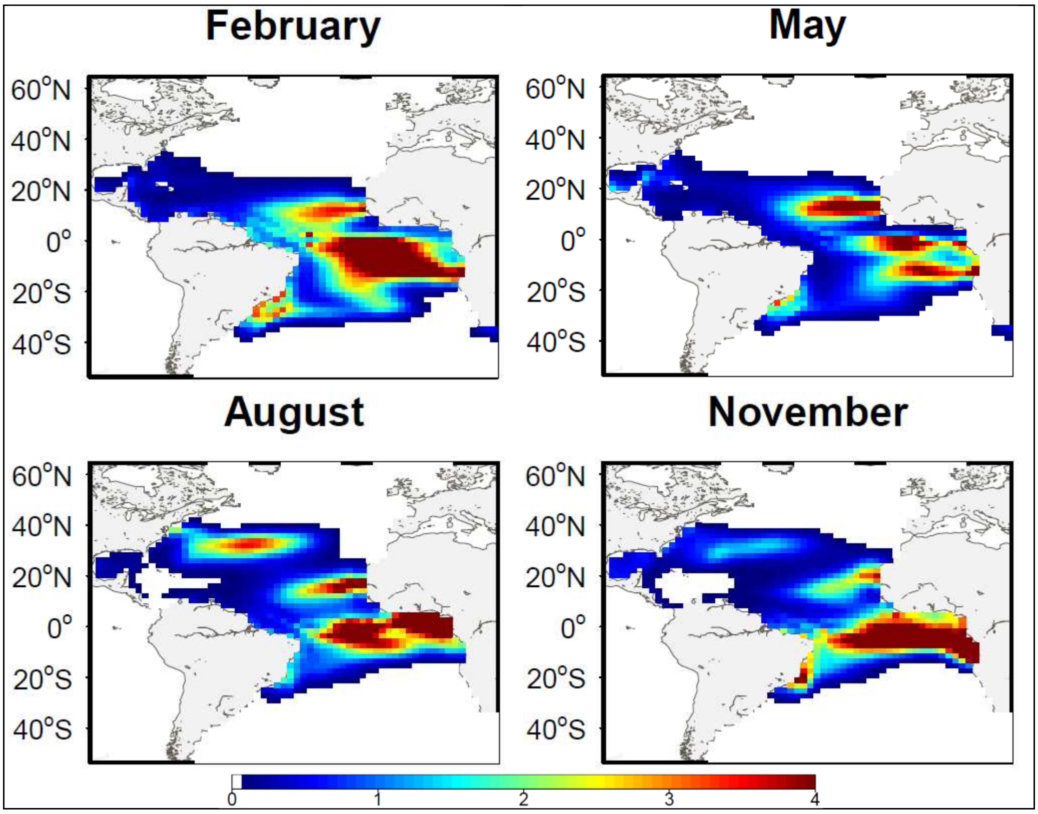

Figure 11 – Seasonal distribution maps of predicted albacore juvenile recruits (Nb m^{-2}).

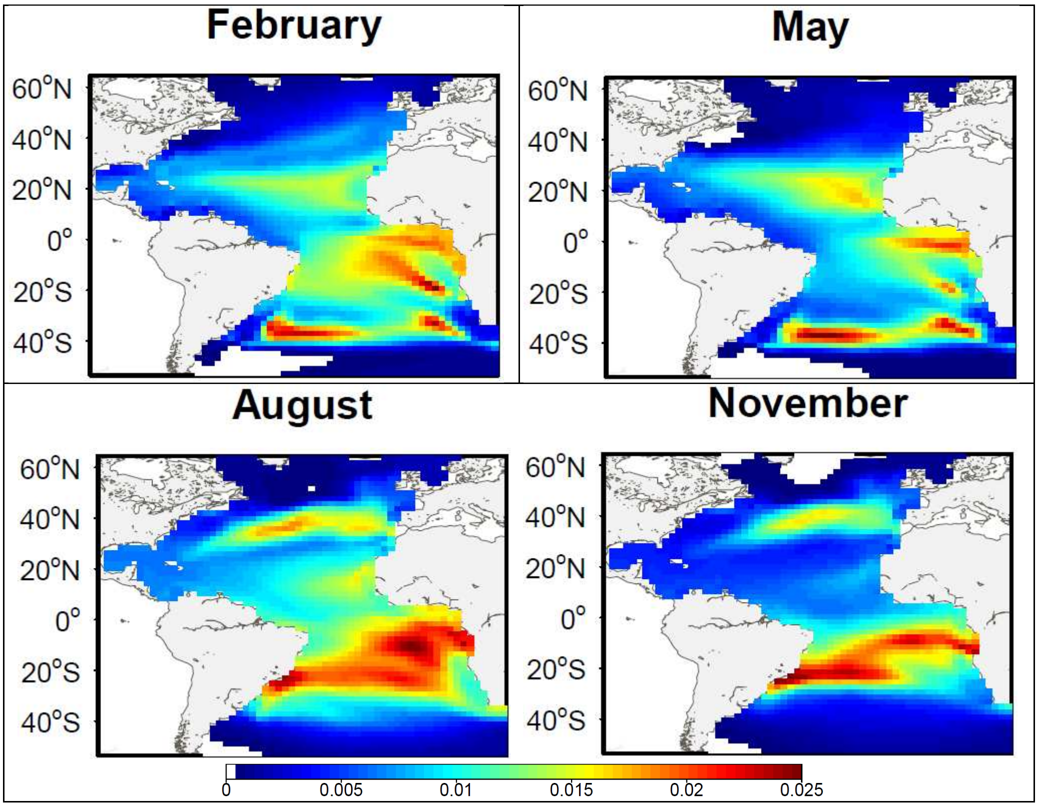

Figure 12 – Seasonal distribution maps of predicted albacore adult biomass (t km^{-2}).

5.2.4. Downscaling to operational configuration

The operational chain of production has been implemented to provide near real time and forecast of mid-trophic functional groups (**Figure 13**), based on primary production derived from satellite ocean colour and the physical fields (temperature and currents) from the Mercator-Ocean PSY3 (1/4°) ocean circulation model. The downscaling of parameterization for albacore population dynamics and fisheries from coarse resolution to the 1/4° x week resolution is currently in progress and will provide the updated parameterization and initial conditions of the population structure to start the tuna operational chain of production.

Several analyses will be conducted to analyse the sensitivity of model outputs to physical forcings and compare the free run and assimilated run of the last ocean reanalysis GLORYS2V4. The impact will be measured on the fit to historical geo-referenced fishing data. In relation with the task in AtlantOS WP5, the validation will also use acoustic (38 kHz) observations (**Figure 14**) that provide a biomass estimate of the mid-trophic level functional groups (micronekton).

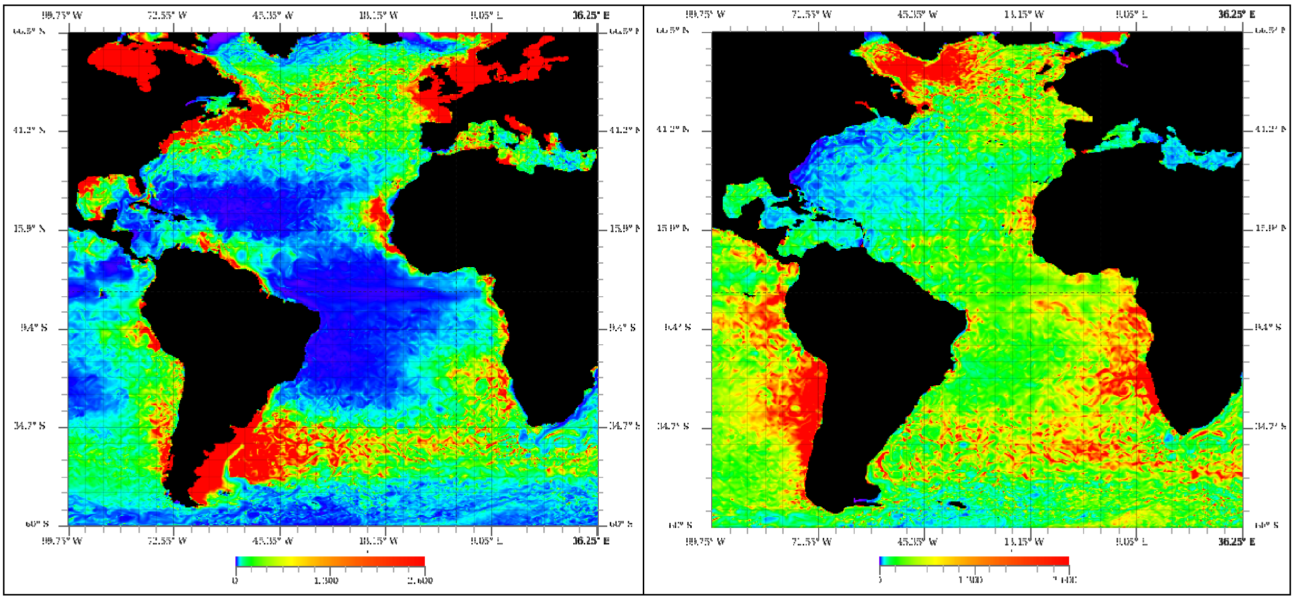

Figure 13 - Weekly biomass (g m-2) distributions (22-29 March 2017) of (left) epipelagic and (right) lower mesopelagic mid-trophic level functional groups predicted with the Mercator-Ocean PSY3 (1/4°) ocean circulation model.

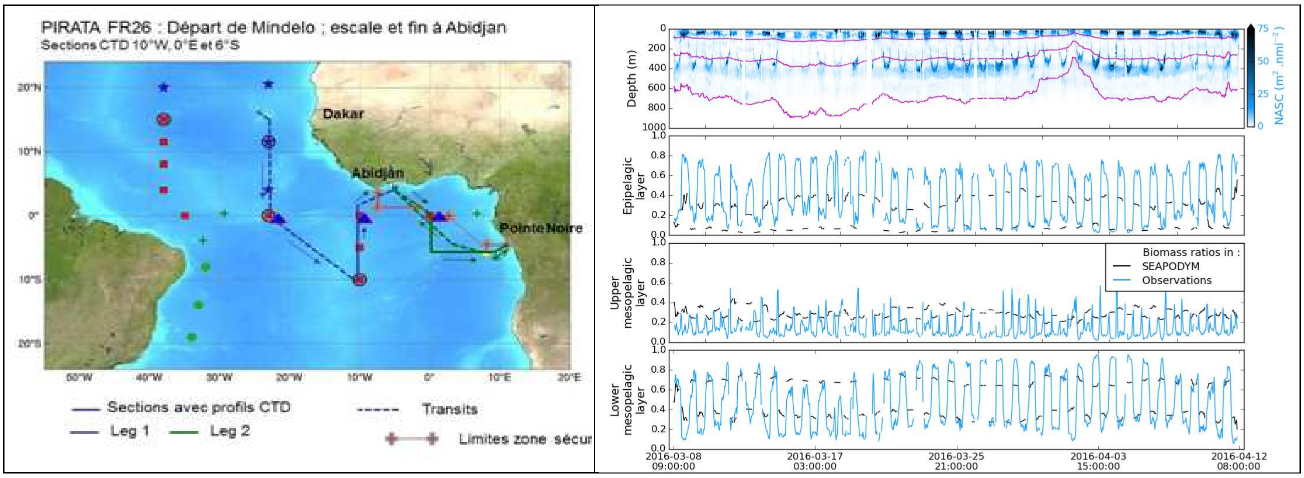

Figure 14 – Left: PIRATA acoustic transects (38 kHz) collected during a maintenance cruise of the PIRATA network. Right: Three vertical layers of the model, and comparison between relative ratio of predicted biomass of micronekton and observed NASC signal in each layer. Note that the model does not simulate transition periods between nighttime and daytime.

6. Work plan and discussion

While Regional Fisheries Management Organizations are increasingly encouraged to address both exploitation and environmental variability issues, there are few examples of new modeling tools that address classical stock assessment questions (best estimates of biomass, natural and fishing mortality) with those related to environmental and climate variability. We used SEAPODYM with the ICCAT historical multinational fishery dataset in order to develop the first pre-operational configuration of a spatially explicit population dynamics model of the Atlantic albacore tuna population and its main fisheries. The optimization of the model and its validation over the historical period of exploitation has been achieved. This is a difficult phase and should be revised and improved in the future, especially to test the impact of new environmental forcing or the introduction of new data in the MLE approach.

Once the ongoing downscaling phase to the ¼° resolution operational forcing is achieved for albacore, it will become possible to run the albacore pre-operational model with a start time in 1998. This is already the case for the micronekton functional groups; a key biological driver essential to simulate albacore dynamics. Then, Atlantic albacore density distributions will be produced automatically in near real time for the different life stages (juveniles, young immature and adult mature). Two chains of production will compute the distributions with and without fishing to provide clear indication of fishing impact separated of the environmental variability (**Figure 9**).

These activities are planned to continue in 2017 (**Figure 15**). By the end of this year, we should be able to deliver the first pre-operational outputs, i.e. density (biomass) maps of juvenile (age 1-3 months), immature (4 – 54 months) and adult (> 54 months) with diagnostic plots showing the fishing impact. Model outputs will be produced using standard NetCDF format and used to update maps on a web site, e.g., AtlantOS or/and EMODNET. In collaboration with colleagues involved in the management of tuna fisheries at ICCAT and FAO, end-user feedback of the pre-operational production of tuna stock distributions will be evaluated in 2018.

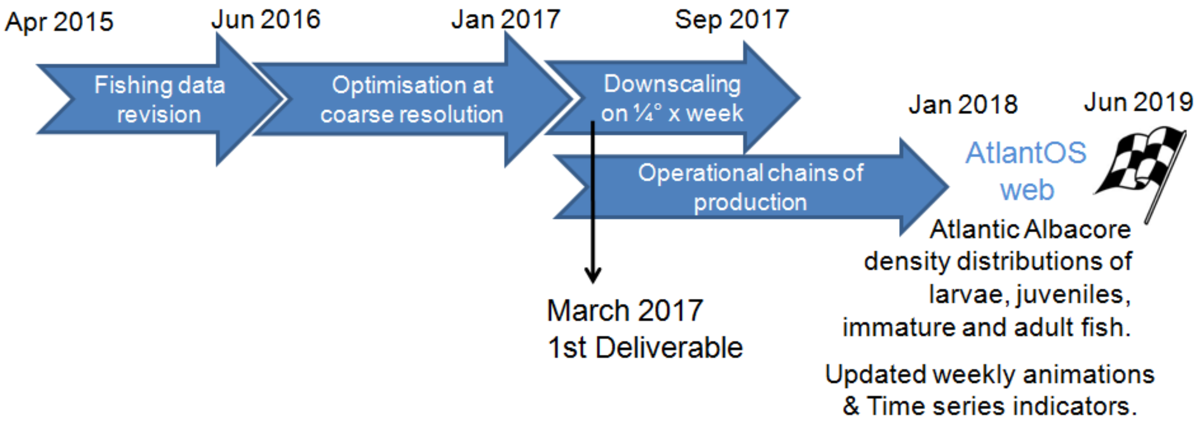

Figure 15 – Gantt chart for the task 8.7: Operational real-time and forecast modeling of Atlantic albacore tuna.

While becoming less dependent on fishing data to estimate fish stock characteristics, the SEAPODYM model outputs on the spatially explicit distribution of fish abundance by cohort are sensitive to the physical drivers, especially 3D currents. The impact of data assimilation in the operational ocean circulation model will be tested; two simulations that use ocean forcing from a recent reanalysis (GLORYS2V4) with and without data assimilation will be compared.

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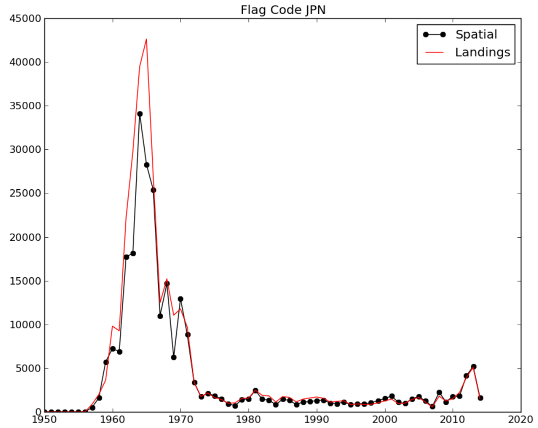
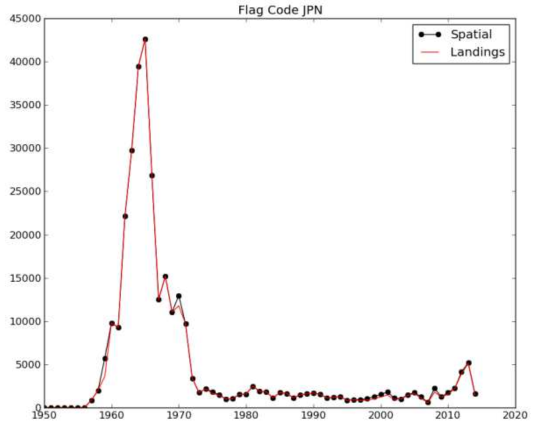
8. Appendix

Annual catch by fleet for nominal and geo-referenced datasets before and after scaling to nominal catch level.

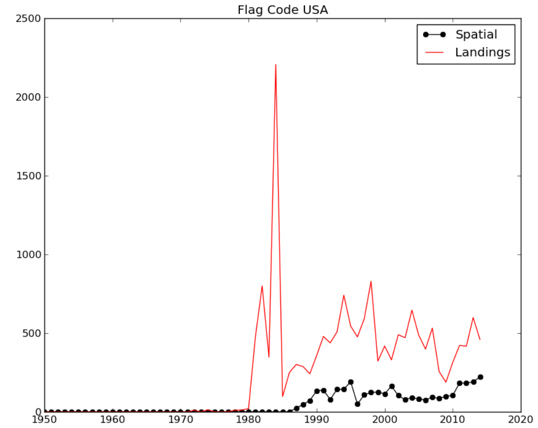
JPN (L1-L2)



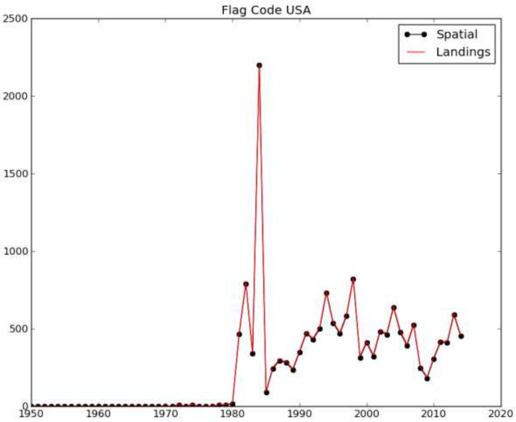
Japan: L1 + L2 +D101



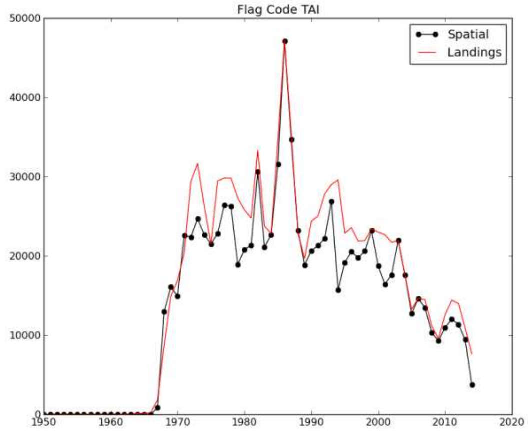
USA (L3)



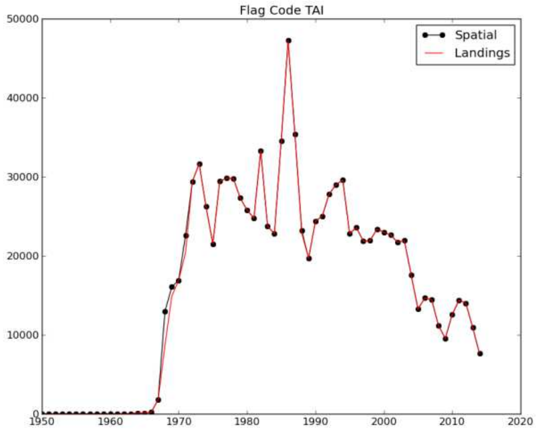
USA: L3 + D102



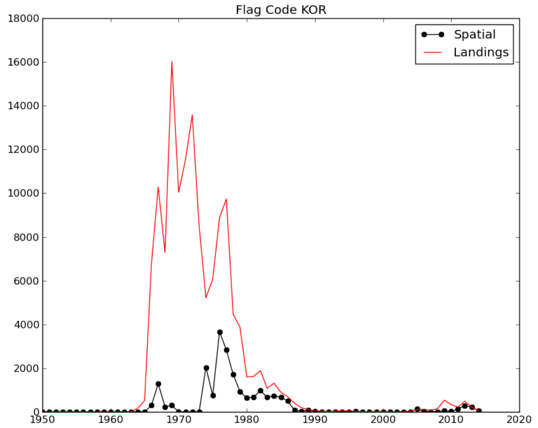
Taiwan (L4, L5, L6, and L7) after removal of outliers for years 1994 and 2001



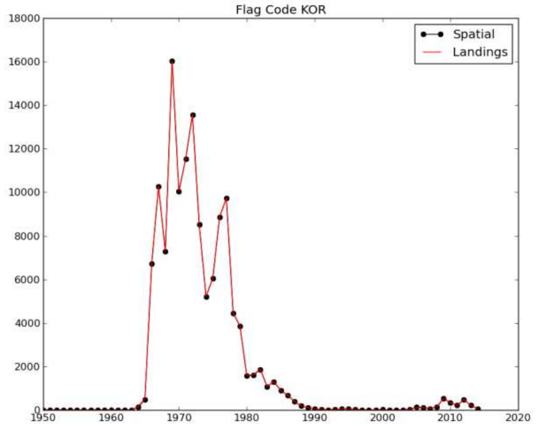
Taiwan : L4+L5+L6+L7+D104



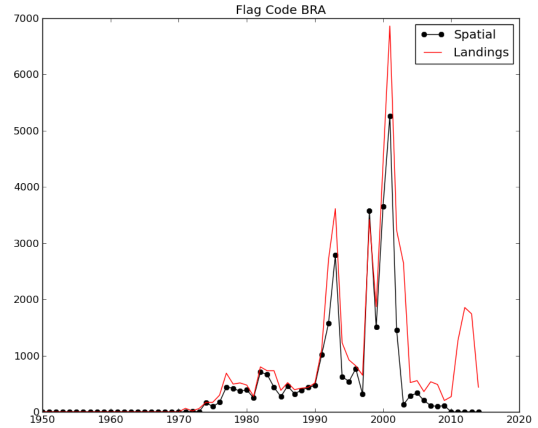
Korea (L8, L9)



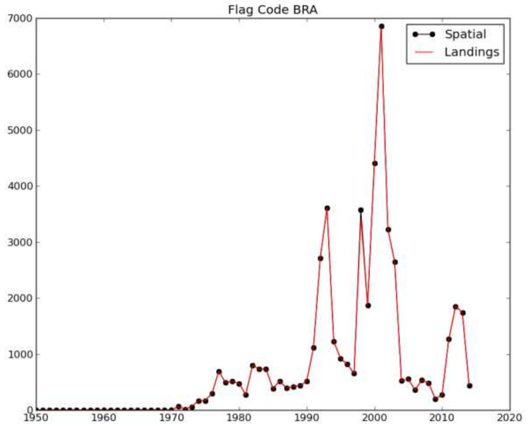
Korea : L8 + L9 +D108



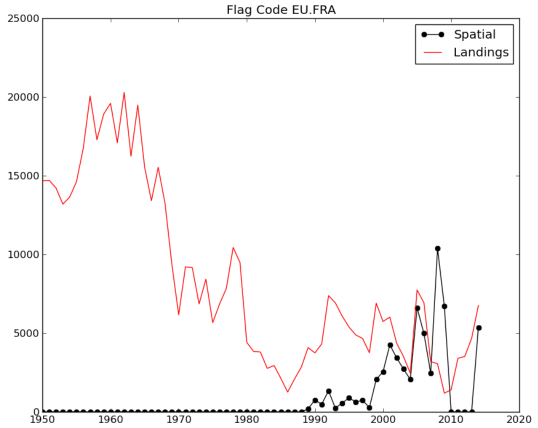
Brazil (L10)



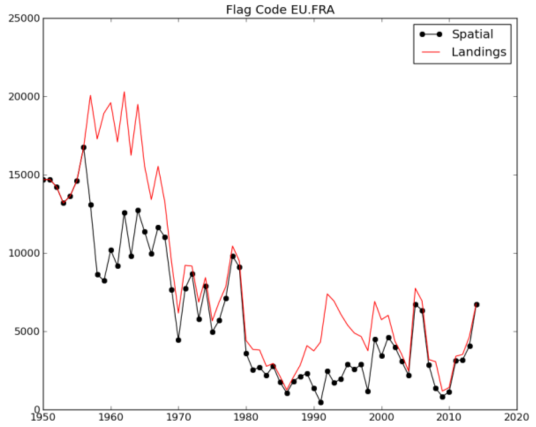
Brazil : L10 + D 110

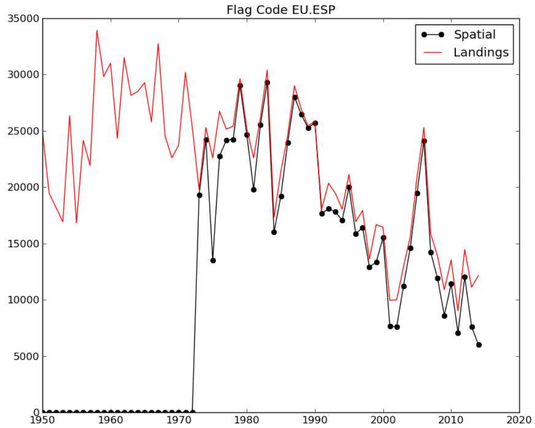
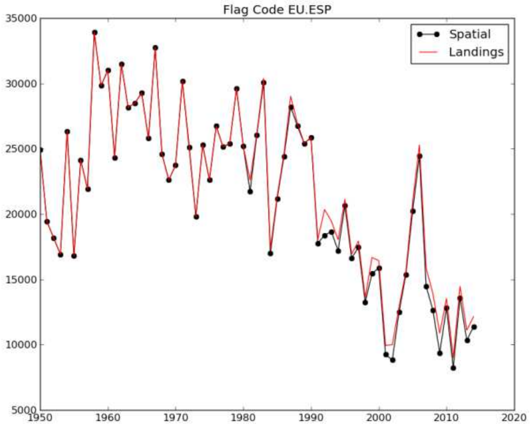
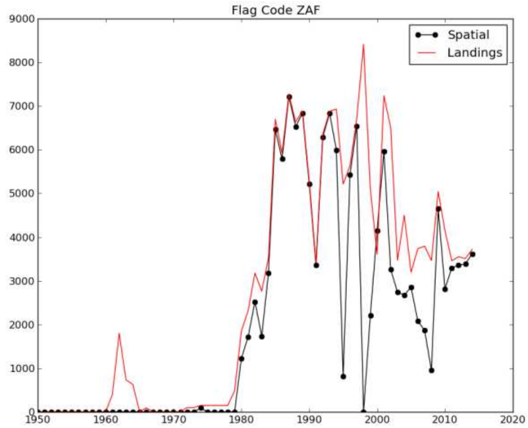
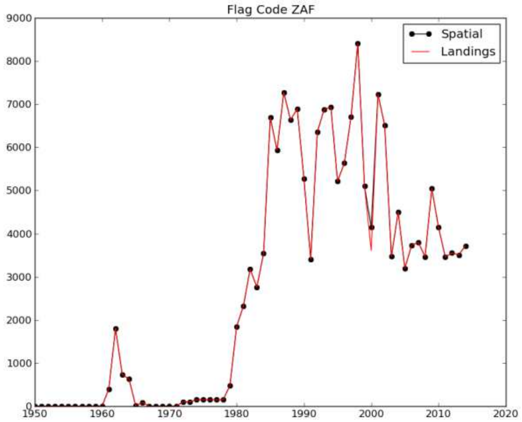
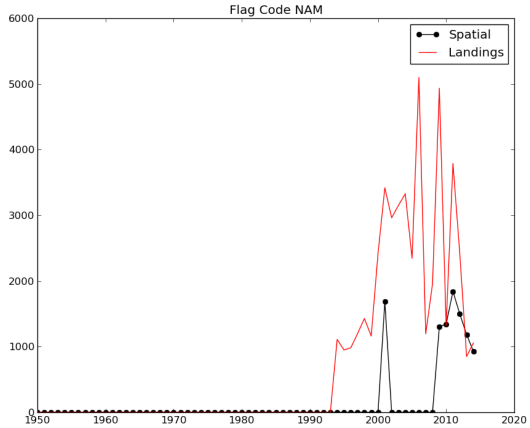


Francia (T11 – T12) : correction years 2008 and 2009 (nr -> kg)



France : T11 +T 12 + D111 + D112



Spain (T13, B14) 	Spain : T13 + B14 +D113 + D114 
South Africa (B15) with correction outliers in 1994 	South Africa : B15 +D115 
Namibia (B16) with outlier correction (Hampel filter in catch) 	Namibia : B16 +D116